Modelling and Optimisation of Oil Palm Biomass Value Chains and the Environment–Food–Energy–Water Nexus in Peninsular Malaysia

Nowilin Rubinsin[a], Wan Ramli Wan Daud[a, b], Siti Kartom Kamarudin[a, b], Mohd Shahbudin Masdar[a, b], Masli Irwan Rosli[a, b], Sheila Samsatli[c], John Frederick D. Tapia[d], Wan Azlina Wan Ab Karim Ghani[e], Azhan Hasan[f], Kean Long Lim[a,*]

[a]Fuel Cell Institute, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

[b]Research Center for Sustainable Process Technology (CESPRO), Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

[c]Department of Chemical Engineering, University of Bath, Claverton Down, Bath BA2 7AH, United Kingdom

[d]Chemical Engineering Department, De La Salle University- Manila, 2401 Taft Avenue, Malate, Manila, 1004, Philippines

[e]Department of Chemical & Environmental Engineering/Sustainable Process Engineering Research Center (SPERC), Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

[f]Department of Management and Humanities, Centre for Sustainable Resources, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 32610, Seri Iskandar, Perak, Malaysia

*Corresponding author; Email: kllim@ukm.edu.my, Tel: 03-8911-8494

ABSTRACT

This study aims to develop a decision model to optimize the oil palm biomass value chains by minimising the environmental impact whiles generating economy value from their bioproducts. The model considers two major components, namely, a fuzzy analytic hierarchy (FAHP) framework and a multi-objective optimisation model. Both components will be used by integrating the priorities of the environmental and economic impacts obtained from experts' judgement with the multi-objective optimisation model to generate an optimal solution based on expert's judgement. The framework used to study different case study for the oil palm industry in Peninsular Malaysia. Results show that a maximum profit of 267,116,398 USD per year can be achieved. However, to minimise the environmental impact, a 34% cut of the profit is needed to reduce 91% of CO_2 emissions generated and 97% of water consumption. Moreover, the model generates optimal pathways by selecting the processing facilities that are needed in the value chain to achieve the objectives. The biomass or bio-product distribution networks around Peninsular Malaysia are also presented in this paper. Several scenarios are discussed to observe the effects on the optimal value chain solutions by manipulating the production level. On the basis of the results, the interactions of the environment–food–energy–water nexus are investigated. Therefore, this study can contribute to the improvement of oil palm industry policies while addressing sustainability issues through the proposed value chain model.

Keywords: Optimisation, oil palm biomass, biomass value chain, nexus

1.0 INTRODUCTION

The palm oil industry is an important and inimitable economic contributor to Malaysia due to the global demand for food and bio-products [1]. The increasing demand for palm oil products is expected to lead to land expansion, and approximately 5 Mha of additional land is required to meet the demand [2]. However, land expansion becomes a great concern in Malaysia as it will lead to environmental issues such as deforestation, biodiversity loss, food chain disruption, water and air pollution and increased CO_2 emissions. Therefore, the sustainability of this industry is critical to overcome the environmental issues [3].

The Malaysian government has developed several policies to help drive the development of renewable energy in order to reduce reliance on fossil fuel consumption and greenhouse gas (GHG) emissions. This concern has led to the development of the Kyoto Protocol and 'Five-Fuel Diversification Policy' in the Eighth Malaysia Plan which emphasize on the utilisation of oil palm biomass could contribute to the reduction of GHG emissions by producing bio-energy products that are more environmentally friendly. The potential of oil palm biomass has led to the development of a few policies [4–6]. For example, the National Biotechnology Policy that was introduced in 2005 aims at boosting the biotechnology industry in Malaysia to provide 5% of gross domestic product (GDP) by 2020 [7]. On 21st March 2006, the National Biofuel Policy was launched to promote the use of palm oil-based biofuel for transportation and power generation [8]. The National Green Technology aims to advance the green technology industry and support biotechnology advancement in Malaysia. This policy also encourages the utilisation of biomass, such as empty fruit bunches (EFB) and biogas [4]. In 2010, the National Renewable Energy Policy and Action Plan was launched as part of the Tenth Malaysia Plan [8]. This policy aims to enhance renewable energy to become the national power source whilst boosting the development of the renewable energy industry [9]. The Biomass Industry Strategic Action Plan focusses on the involvement of small and medium enterprises in high-value utilisation of biomass. During the implementation of this policy, the Malaysia Biomass Industries Confederation (MBIC) and Bio-economy Transformation Programme (BTP) were formed [4]. The BTP was implemented to further develop the bio-based industry in Malaysia [10]. The National Biomass Strategy 2020 was launched in 2013 and seen as a game changer by power producers. This strategy offers the country a way to meet renewable energy sources by utilising biomass and outlines the action plans and opportunities in biomass value chain development [11]. Due to the increasing capacity of the oil palm sector in Malaysia, the National Biomass Strategy 2020 remains focused in making full utilisation of oil palm biomass [12].

In order to improve the sustainability of the oil palm industry, oil palm biomass must be managed and utilised properly to generate wealth whilst minimising wastes [13]. Oil palm biomass has emerged as a potential contributor to renewable energy sources and to the production of value-added products. The biomass generated in oil palm processing mills includes EFB, palm kernel shells (PKS), mesocarp fibres and palm oil mill effluent (POME). The biomass generated in mills is based on fresh fruit bunch (FFB) extraction. The amount of EFB and PKS produced is estimated to be 22% and 7% of FFB, respectively, whereas POME is produced at 0.7 tonne per tonne of FFB [14]. Based on the FFB yield data provided by the Malaysian Palm Oil Board, the average amount of oil palm biomass availability in Malaysia from 2017 to 2019 is approximately 22.42 million tonnes of EFB, 7.13 million tonnes of PKS and 71.34 million tonne of POME. As of February 2020, the amount of EFB, PKS and POME generated is approximately 2.80 million tonnes, 0.89 million tonnes and 8.92 million tonne, respectively. Due to the huge amount of oil palm biomass generated yearly, Malaysia can potentially utilise the biomass to produce value-added products. One of the challenges in considering oil palm biomass as energy sources is to utilise the biomass efficiently and effectively in order to reduce the cost of supply chain and the process to convert it into useful products. There are many advantages in converting oil palm biomass into valuable products, but several barriers need to be considered, including transportation and production costs, logistic efficiency, quality and environmental impacts [13,15]. Therefore, to overcome these challenges, the development of a biomass value chain is essential to bring positive impacts into the industry. Moreover, the importance of 'waste to wealth' is increasingly being recognised in Malaysia [16].

Several studies have investigated the biomass value chain in Malaysia. According to the optimised model of Shukery et al. [17], maximising economic benefits and minimising wastes through multi-objective linear programming (LP) model has the highest efficiency in producing various types of products. Theo et al., [18] has successfully created revenue from POME and biomass utilisation by adopting a fuzzy optimisation method. Meanwhile, BeWhere model developed by Hoo et al. [19] was used to identify the potential of injection of bio-methane from POME into the natural gas grid. Wu et al. [20] investigated the potential of palm solid wastes and biogas to produce renewable fuel and electricity using the ECLIPSE software. Optimal production levels of high-value products with economic objectives were studied by Abdulrazik et al., [21]. Their model was developed to optimise oil palm EFB using LP. All of these studies can help determine the potential of oil palm biomass to produce bio-products and bio-energy products. Many of them used multiple biomass feedstocks or technologies to produce products, but limited information is available on the palm oil mills and technologies. This gap was filled by our previous study Rubinsin et al.,2 [22] where only a single biomass feedstock was considered. However, incorporated geographic information system (GIS) locations of palm oil mills and processing facilities in Malaysia and integrated model with the incorporation of expert knowledge into the multi-objective optimisation model provide a new approach in the oil palm value chain analyses [23]. The study revealed that capturing experts' view needs to be included in the value chain as indicated an important criteria for best practice for the oil palm industry by several other studies [24–26] also indicated that capturing experts' judgement is the best practice for the oil palm industry. Ngan et al. [27] used the fuzzy analytic network process (FANP) method to consider human factors in their study and found that it provides a feasible solution to the industry. In another study of [28], they also suggested that incorporating stakeholders in risk management could help in evaluating risk mitigation strategies in the industry.

The present study aims to provide a multi-objective optimisation model with the incorporation of expert-based judgement. The multi-objective optimisation model is an extension work of our previous study of Rubinsin et al.., 2019 but with the addition of two types of oil palm biomass of PKS and POME with the incorporation of expert-based judgement that previously investigated by Tapia and Samsatli, 2019. Therefore this study will investigate the oil palm biomass value chain in Peninsular Malaysia as the pilot study with the characteristics as follows: (1) considering the utilisation of different oil palm biomass to generate multiple bio-products based on the palm oil mills and processing facilities GIS locations in Peninsular Malaysia, (2) incorporating expert knowledge in the optimised model and (3) capturing the impacts of biomass value chains on the environment–food–energy–water (EFEW) nexus. Therefore, this study could help address issues in the planning systems of oil palm biomass where perceptions of the stakeholders and owners of the company were integrated into the planning system. In addition, more biomass policies could be developed to improve the industry's sustainability.

2.0 BIOMASS VALUE CHAIN MODEL DEVELOPMENT

The biomass value chain model develop using the sequential steps shown in Figure 2.1. Figure 2.1 (a) is a decision tool to determine the priorities between environmental and economic impacts and Figure 2.1(b) shows the multi-objective oil palm biomass value chain model. Both components are the integration between the methods proposed by Tapia and Samsatli, (2019) and our previous study Rubinsin et al.,2020 to generate an optimal solution based on the expert for the value chain.

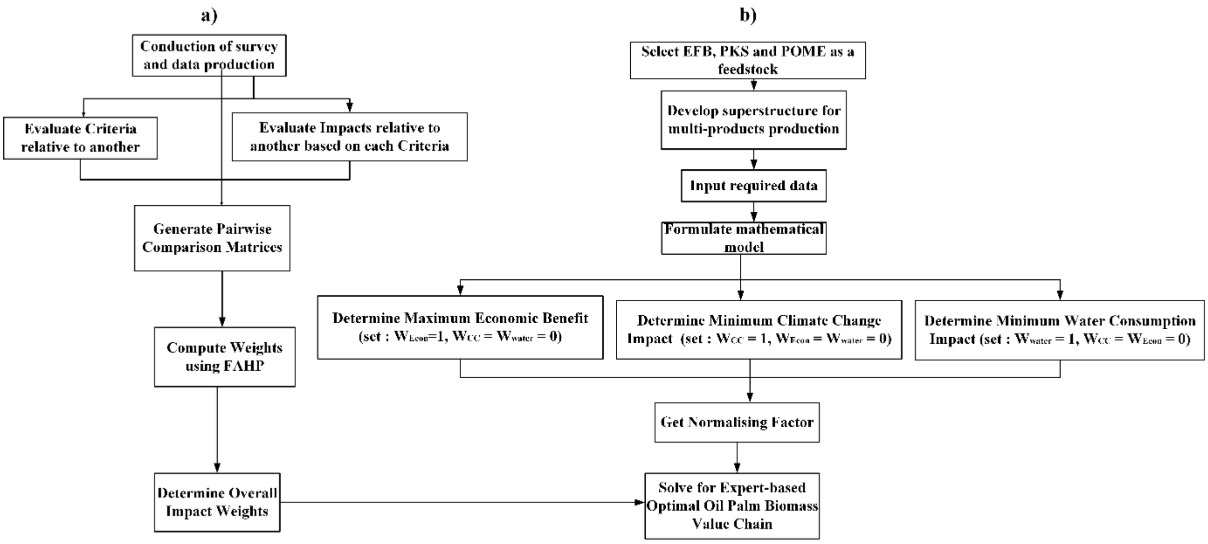


Figure 2.1 Sequential optimisation steps of oil palm biomass value chain a) Fuzzy Analytic Hierarchy Process (FAHP) b) Multi-Objective Oil Palm Biomass Value Chains

2.1 Fuzzy Analytic Hierarchy Process (FAHP) Decision Model

The hierarchical value chain decision structure with three decision levels is presented in Figure 2.2. The first level is the goal, the second one is the criteria and the third level is the impacts or the objectives. The goal of the value chain is to decide the impact priorities in the value chain model based on three criteria that are short-term and long-term benefits, policy development and social acceptance. Three impacts including economic, climate change and water impact of the above mentioned criteria will be investigated. In this study, the economic impact is the transportation and production cost, The climate change impact and water impact were considered as an environmental impact. The climate change is the CO_2 emissions generated, and water impact is the water footprint or water consumption in the value chain. As can be seen in Figure 2.2, the decision of each level is represented by an arrow, which required expert judgement as an input. The expert judgements of each decision level are translated into priority weight with respect to the input level. For example, the arrows directing from goal to criteria level indicates the priority weight of criteria with respect to goal; same goes to the arrows between impact and criteria level. The overall priority weights are computed based on the priority weights of the criteria and impacts. The priority weights are obtained using the qualitative value judgement given by the Malaysian experts in palm oil related industry. The description of the expert judgment criteria are as follows:

- Short-term benefits: The experts are consulted on the priority of economic, climate change and water impact during the deployment and operation of value chain model at its early stage.

- Long-term benefits: The same impacts as above were consulted to the experts when the value chain model becomes well established in the future and its potential impact to the palm oil industry in a long run.

- Policy development: The experts are asked to consider to prioritising the abovementioned impacts in introducing new economic and environmental strategies and policies for palm oil industry. The aim is to maximise the economic benefits without overlooking the environmental impacts. This enables the model to generate useful insights during policy development in the future.

- Social acceptance: The impact evaluations are based on the overall public acceptance on the high-value bioenergy and bio-based products from the oil palm biomass value chain and its potential social benefits, especially on the job creation to the low income indigenous community.

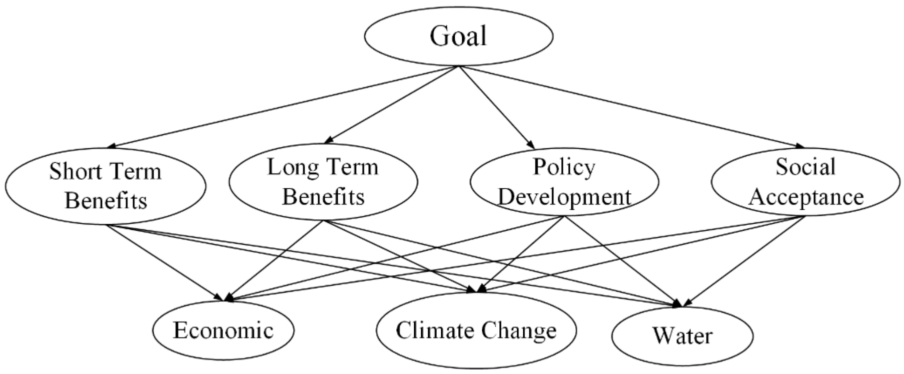


Figure 2.2 Decision Structure of the Value Chain

To obtain the experts' view regarding the importance of the objectives in the value chain, two categories of pairwise comparison matrices from experts are evaluated. The first category is the pairwise judgement between impacts based on the criteria. This category is used to determine qualitatively the priority weights of each impact based on expert judgement. The second category is the pairwise comparison between criteria. An example of pairwise comparison matrix with qualitative judgements on impacts (i.e. economic, climate change and water) in each criterion (short term benefit, long term benefit and policy development) and their corresponding TFNs are presented in Table 2.1, Appendix A.1.

The expert qualitative judgements are given as either 'equally' (EQ), 'slightly more' (SM), 'moderately more' (MM), 'strongly more' (ST) or 'very strongly more' (VS) important than other. The corresponding opposing qualitative judgement is the same for EQ, 'slightly less' is

1/SM, 'moderately less' is 1/MM, 'strongly less' is 1/ST, and 'very strongly less' is 1/VS. Their equivalent quantitative judgement is given as triangular fuzzy number (TFN) given in Table 2.2 with their lower, model and upper numbers. Both lower bound and upper bound values denote the least possible equivalent of the qualitative judgement, while the modal value denotes the most possible equivalent of the qualitative judgement. The membership functions for each qualitative judgement are presented in Figure 2.3, where it can be seen that the stronger the judgement is, the wider the gap between the upper and the lower bound. We adopted the calibration scales developed by Promentilla et al. [30] and Ishizaka and Nguyen [31] which using the scaling method of Saaty's 9-point scale for pairwise comparison [32].

Table 2.2 Qualitative judgement and their TFN.

Qualitative judgement	Lower	Modal	Upper
EQ	1	1	1
SM	1.2	2	3.2
MM	1.5	3	5.6
ST	3	5	7.9
VS	6	8	9.5
1/SM	0.31	0.5	0.83
1/MM	0.18	0.33	0.67
1/ST	0.13	0.2	0.33
1/VS	0.11	0.13	0.17

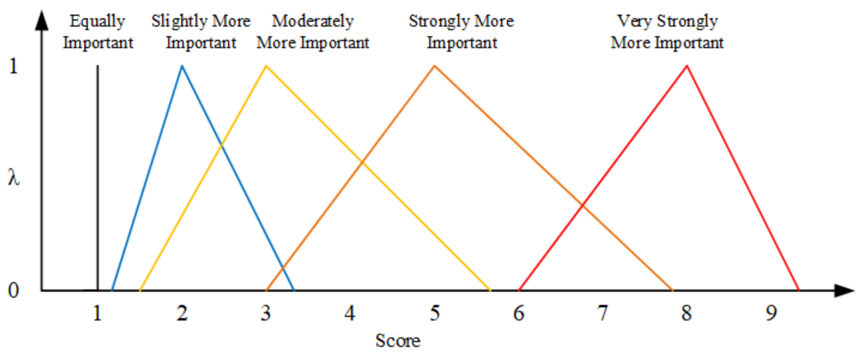


Figure 2.3 Illustration of triangular fuzzy numbers with their respective membership functions

The priority weights are derived from the following optimisation model developed by Promentilla et al., [33] and Tapia and Samsatli [29] by maximising λ in Eq. (1), which includes the overall judgement consistency, subjected to the respective membership functions.

$$\text{Maximize } \lambda \tag{1}$$

$$a_{qq'} - l_{qq'} \geq \lambda\left(m_{qq'} - l_{qq'}\right);\ a_{q'q} - l_{q'q} \geq \lambda\left(m_{q'q} - l_{q'q}\right) \qquad \forall\,(q',q)|q < q' \tag{2}$$

$$u_{qq'} - a_{qq'} \geq \lambda\left(u_{qq'} - m_{qq'}\right);\ u_{q'q} - a_{q'q} \geq \lambda\left(u_{q'q} - m_{q'q}\right) \qquad \forall\,(q',q)|q < q' \tag{3}$$

$$a_{qq'} = \frac{w_q}{w_{q'}};\ a_{q'q} = \frac{w_{q'}}{w_q} \qquad \forall\,(q',q)|q < q' \tag{4}$$

$$\sum_q w_q = 1 \tag{5}$$

The priority weights (w_q) of criterion or impact from a designated pairwise comparison matrix are calculated with these optimisation models, with the inputs from the lower bound value ($l_{qq^{'}}$), model value ($m_{qq^{'}}$) and upper value ($u_{qq^{'}}$) of a criterion or impact (q) with reference to another criterion or impact ($q^{'}$). The non-fuzzy (crisp) judgement ($a_{qq^{'}}$) is reported as the ratio between the priority weights of q and $q^{'}$. The aim of solving this set of judgments is to ensure λ to attain the highest possible consistency, which is close to 1 An example of solution to the priority weights of the pairwise comparison matrix of impacts in Table 2.1, Appendix A.1, are 0.043 (economic), 0.834 (climate change) and 0.113 (water), respectively with a fuzzy consistency λ of 0.481. The model is also capable to solve incomplete judgement, provided that each criterion or impact is considered in at least one judgement with at least n – 1 judgements, where n is the number of criterion or impact. The overall weights of each impact are determined using Eq. (6).

$$w_{im} = \sum_c C_c S_{im,c} \tag{6}$$

$S_{\mathrm{im,c}}$ represents the priority weight of impact (im), and C_{c} represents the priority weight of criterion (c). The weighted sum (w_{im}) is determined and applied in the value chain model.

2.2 Multi-objective Oil Palm Biomass Value Chains

The objective function for the model is the weighted sum of the impacts of production and transportation from every processing facility, as shown in Eq. (7).

$$\text{Minimize impact} = \min \textstyle\sum_{im} w_{im} NF_{im}\left(TIP_{im} + PIP_{im} - RP_{im,}\right) \tag{7}$$

The aim of this objective function is to minimise the overall impact of production and transportation by subtracting the revenue generated (RP_{im}) from the value chain. PIP_{im} is the total production impact from all products, and TIP_{im} is the total transportation impact of the transported product between processing facilities. The normalisation factor (NF_{im}) is determined from the ratio between the best value of economic impact and the impact value being minimised. The impacts of each objectives are aggregated based on the numerical weights(w_{im}). Varying the following numerical weights with the corresponding units of objective function enables different objectives to be set:

- Maximise profit (in million MYR): set w_{Economic}= 1,$w_{\mathrm{Climate\ Change}}$= 0 and w_{Water}= 0

- Minimise climate change impact (in million tonne CO_2eq): set w_{Economic}= 0, $w_{\mathrm{Climate\ Change}}$= 1 and w_{Water}= 0

- Minimise water impact (in million m^3): set $w_{Economic} = 0$, $w_{Climate\ Change} = 0$ and $w_{Water} = 1$

$$RP_{im} = \sum_{p=1}^{p} \mathrm{QS_p} \times \text{Selling price} \quad (8)$$

The RP_{im} in Eq. (7) is calculated using Eq. (8). The total revenue is the summation product of sold products ($\mathrm{QS_p}$) and their selling price (listed in Appendix, Table B.1). The TIP_{im} in Eq. (7) of the value chain is expressed as follows:

$$TIP_{im} = TIB_{im} + TII_{im} + TIK_{im} + TIM_{im} \quad \forall_{\mathrm{im}} \quad (9)$$

The transportation impact resulting from biomass utilisation and product transported between processing facilities is calculated using Eq. (9). TIB_{im} is the total transportation impact from biomass utilisation from mills (g) to pre-processing facilities (h). TII_{im} is the overall transportation impact of pre-processed feedstocks (i) transported to main processing facilities (j). TIK_{im} is the transportation impact of intermediate product 1 (k) transported to further processing facilities (l). TIM_{im} is the total transportation impact of intermediate product 2 (m) transported to further processing facilities 2 (n). Note that the water impact in transportation is assumed to be negligible. Therefore, the transportation impact are consists of economic and climate change impact only. The transportation impact of biomass transported from palm oil mills to pre-processing facilities is expressed as follows:

$$TIB_{im} = \textstyle\sum_{b,g,h} (FTB_{b,g,h} \times \mathrm{SFB_{b,g,h,i,im}}) + (FTB_{b,g,h} \times \mathrm{TFB_{b,g,h,im}}) + (FTB_{b,g,h} \times ETFB_{b,g,h,im}) \quad \forall_{\mathrm{im}} \quad (10)$$

In Eq. (10), the amount of biomass ($FTB_{b,g,h}$) transported from mills (g) to pre-processing facilities (h) is multiplied by the selling price, transportation cost factor and transportation CO_2 emission factor to obtain the total transportation impact. The biomass selling price ($\mathrm{SFB_{b,g,h,im}}$) is used to obtain the total biomass cost. The biomass selling price is listed in Table B.1. $\mathrm{TFB_{b,g,h,im}}$ is the transportation cost factor used to calculate the transportation cost of biomass, and $\mathrm{ETFB_{b,g,h,im}}$ denotes the transportation CO_2 emission factor in obtaining the total CO_2 emission generated from biomass transportation. The transportation cost factors and emission factors for biomass transported from mills to pre-processing facilities are listed in Table B.2.

The transportation impact of pre-processed feedstocks (i) transported from pre-processing facilities (h) to main processing facilities (j) is expressed as follows:

$$TII_{im} = \textstyle\sum_{b,g,h,i,j} (FTI_{b,g,h,i,j} \times \mathrm{TFI_{b,g,h,i,j,im}}) + (FTI_{b,g,h,i,j} \times \mathrm{ETFI_{b,g,h,i,j,im}}) \quad \forall_{\mathrm{im}} \quad (11)$$

The amount of transported pre-processed feedstocks ($FTI_{b,g,h,i,j}$) in Eq. (11) is multiplied by the transportation cost factor ($\mathrm{TFI_{b,g,h,i,j,im}}$) and transportation CO_2 emission factor ($\mathrm{ETFI_{b,g,h,i,j,im}}$) to obtain the total transportation cost and CO_2 emissions generated, respectively. The transportation cost factors and emission factors for pre-processed feedstocks (i) transported from pre-processing facilities (h) to main processing facilities (j) are listed in Table B.3.

The transportation impact of intermediate products 1 (k) transported from main processing facilities (j) to further processing 1 facilities (l) is expressed as follows:

$$TIK_{im} = \sum_{j,k,l}(FTK_{j,k,l} \times \mathrm{TFK_{j,k,l,im}}) + (FTK_{j,k,l} \times \mathrm{ETFK_{j,k,l,im}}) \qquad \forall_{\mathrm{im}} \qquad (12)$$

In Eq. (12), the amount of intermediate products 1 transported ($FTK_{j,k,l}$) will then be multiplied by the transportation cost factor ($\mathrm{TFK_{j,k,l,im}}$) and transportation CO_2 emission factor ($\mathrm{ETFK_{j,k,l,im}}$) to obtain the total transportation cost and CO_2 emissions generated, respectively. The transportation cost factor and emission factor for intermediate products 1 (k) transported from main processing facilities (j) to further processing 1 facilities (l) are listed in Table B.4.

The transportation impact of intermediate products 2 (m) transported from further processing 1 facilities (l) to further processing 2 facilities (n) is expressed as follows:

$$TIM_{im} = \sum_{l,m,n}(FTM_{l,m,n} \times \mathrm{TFM_{l,m,n,im}}) + (FTM_{l,m,n} \times \mathrm{ETFM_{l,m,ni,im}}) \qquad \forall_{\mathrm{im}} \qquad (13)$$

The amount of products transported ($FTM_{l,m,n}$) in Eq. (13) is multiplied by the transportation cost factor ($\mathrm{TFM_{l,m,n,im}}$) and transportation CO_2 emission factor ($\mathrm{ETFM_{l,m,n,im}}$) to obtain the total transportation cost and CO_2 emissions generated, respectively. The transportation cost factors and emission factors for intermediate products 2 (m) transported from further processing 1 facilities (l) to further processing 2 facilities (n) are listed in Table B.5. All transportation cost factors can be determined using equation provided in Appendix A.2.

The production impact (PIP_{im}) resulting from the product produced from every processing facility is shown in Eq. (14).

$$PIP_{im} = PII_{im} + PIK_{im} + PIM_{im} + PIO_{im} \quad \forall_{\mathrm{im}} \qquad (14)$$

PII_{im} is the total production impact of pre-processed products (i) produced in pre-processing facilities (h). PIK_{im} is the total production impact of intermediate products 1 (k) produced in main processing facilities (j). PIM_{im} is the total production impact of intermediate products 2 (m) produced in further processing 1 facilities (l) and PIO_{im} the total production impact of final products (o) produced in further processing 2 facilities (n). The production impact will consider economic, climate change and water impact. The production impact of pre-processed feedstocks in pre-processing facilities is expressed as follows:

$$PII_{im} = \sum_{b,g,h,i}(FPI_{\,b,g,h,i} \times \mathrm{PFI_{b,g,h,i,im}}) + (FPI_{\,b,g,h,i} \times \mathrm{EPFI_{b,g,h,i,im}}) + (FPI_{\,b,g,h,i} \times \mathrm{WFI_{b,g,h,i,im}}) \quad \forall_{\mathrm{im}} \tag{15}$$

In Eq. (15), PII_{im} is the production impact of pre-processed products (i) produced in pre-processing facilities (h). The amount of products ($FPI_{\,b,g,h,i}$) is multiplied by the production cost factor ($\mathrm{PFI_{b,g,h,i,im}}$), production emission factor ($\mathrm{EPFI_{b,g,h,i,im}}$) and water footprint ($\mathrm{WFI_{b,g,h,i,im}}$) to obtain the total production cost, total production CO_2 emission and production water consumption, respectively. The production impact factors are listed in Table B.10.

$$PIK_{im} = \sum_{i,j,k}(FPK_{\,i,j,k} \times \mathrm{PFK_{i,j,k,im}}) + (FPK_{\,i,j,k} \times \mathrm{EPFK_{i,j,k,im}}) + (FPK_{\,i,j,k} \times \mathrm{WFK_{i,j,k,im}}) \quad \forall_{\mathrm{im}} \tag{16}$$

PIK_{im} in Eq. (16) is the production impact of intermediate product 1 (k) produced in the main processing facilities (j). The amount of products ($FPK_{\,i,j,k}$) will be multiplied by the production cost factor ($\mathrm{PFK_{i,j,k,im}}$), production emission factor ($\mathrm{EPFK_{i,j,k,im}}$) and water footprint ($\mathrm{WFK_{i,j,k,im}}$) for water impact to obtain the total production cost, total production CO_2 emission and production water consumption, respectively. The production impact factors are listed in Table B.11.

$$PIM_{im} = \sum_{k,l,m}(FPM_{\,k,l,m} \times \mathrm{PFM_{k,l,m,im}}) + (FPM_{\,k,l,m} \times \mathrm{EPFM_{k,l,m,im}}) + (FPM_{\,k,l,m} \times \mathrm{WFM_{k,l,m,im}}) \quad \forall_{\mathrm{im}} \tag{17}$$

In Eq. (17), PIM_{im} is the production impact of intermediate product 2 (m) produced in further processing 1 facilities (l). The amount of products ($FPM_{\,k,l,m}$) will be multiplied by the production cost factor ($\mathrm{PFM_{k,l,m,im}}$), production emission factor ($\mathrm{EPFM_{k,l,m,im}}$) and water footprint ($\mathrm{WFM_{k,l,m,im}}$) to obtain the total production cost, total production CO_2 emission and production water consumption, respectively. The production impact factors are listed in Table B.12.

$$PIO_{im} = \sum_{m,n,o}(FPO_{\,m,n,o} \times \mathrm{PFO_{m,n,o,im}}) + \left(FPO_{\,m,n,o} \times \mathrm{EPFO_{m,n,o,im}}\right) + (FPO_{\,m,n,o} \times \mathrm{WFO_{m,n,o,im}}) \ \forall_{\mathrm{im}} \tag{18}$$

In Eq. (18), $PIPO_{im}$ is the production impact of the final product (o) produced in further processing 2 facilities (n). The amount of products ($FPO_{\,m,n,o}$) will be multiplied by the production cost factor ($\mathrm{PFO_{m,n,o,im}}$), production emission factor ($\mathrm{EPFO}_{m,n,o}$) and water footprint ($\mathrm{WFO_{m,n,o}}$) to obtain the total production cost, total production CO_2 emission and production water consumption, respectively. The production impact factors are listed in Table

B.13. The amount of product produced at each processing facilities can determined using mass balance equation provided in Appendix A.3.

Eqs. (19) to (21) are the constraints of the model, where these constraints define the boundaries of the model.

$$\sum_{b,g,h} FTB_{g,h} \leq \text{Biomass Availability} \quad \forall_{g} \tag{19}$$

$$Product\ or\ Biomass\ Transport \leq \text{Processing Facilities Capacities} \quad \forall_{g,p} \tag{20}$$

$$\text{Five percent of World Demand} \geq QP_p \geq \text{Product Demand} \quad \forall_{p} \tag{21}$$

The first constraint is on the biomass availability stated in Eq. (19), the total amount of biomass transported ($FTB_{g,h}$) from the palm oil mills is limit by the total availability in the mills. The computed biomass availability of each facilities is listed in Table B.14. The second constraint in Eq. (20) restricts the amount of biomass or products transported to the processing facilities by the capacity of processing facilities. The processing facilities capacities are listed in Appendix, Table B.15. The third constraint in Eq. (21) is to define the production amount of each product (QP_p), which must be in the range of the minimum and maximum of product demand. The product demand are listed in Appendix, Table B.16. All terms used in equations are described in Table B.17.

3.0 RESULTS AND DISCUSSION

3.1 Malaysia Palm Oil Industry Case Study

In Malaysia, the valorisation of the oil palm solid waste into value-added products is still at its infancy, and a lot of works and research need to be done. The typical utilisation of EFB, PKS and POME is shown in Figure 3.1. This typical utilisation involves the pathways used before the optimisation. EFB and PKS are often incinerated, and the ashes will be used as fertiliser. However, open burning is banned by the government due to air pollution. EFB and PKS are commonly utilised as solid fuel for power generation. EFB is typically air-dried to reduce moisture or undergoes pre-treatment, such as pressing and shredding, before being fed into the boiler. PKS is preferable as a fuel due to its low moisture content and high calorific value compared with EFB. EFB contains essential plant nutrients that can be used as organic mulch and compost in plantations. It is also fortified with other bio-based pesticides and disease control compounds that can be sold as a bio-fertiliser for agriculture use. EFB and PKS are often converted to briquette or pellet to increase their combustion rate. These products have a great potential for the economic growth in Malaysia [13,34]. At the international level, these products are often exported to Europe and Asia in response to the high demand and attractive prices [35]. Malaysia is currently a pellet supplier to Korea and Japan [1]. Due to the importance of supply stability, Japan now focuses on alternative biofuels such as EFB and PKS pellets. EFB can also be used as a feedstock for the production of dried long fibre (DLF), which will be used to produce mattresses and cushions, pulp and paper as well as composites for furniture [36]. For POME utilization to mitigate methane emissions, there are 125 biogas power generation plants in Malaysia, whilst other mills still adopt an open lagoon system. Also, there are about 75 mills composting plants under methane avoidance category which utilise 90%-100% of POME or co-composting EFB and POME [36–38].

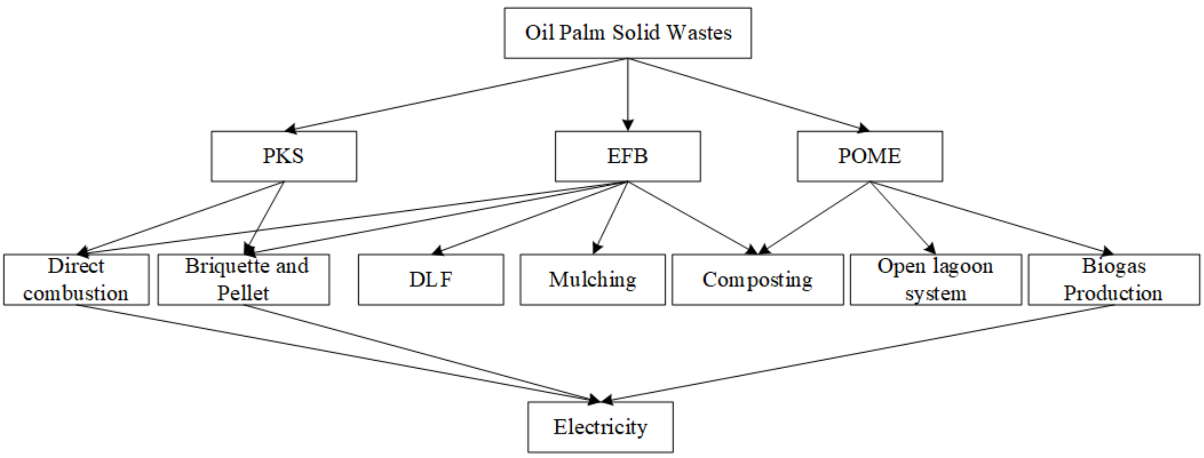


Figure 3.1 Typical Oil Palm Waste Management

The value chain pathway considered for the study is shown in Figure 3.2. In the superstructure, the squares represent the processing facilities, and the ovals represent the products. The solid line shows the processing sequences, and the dashed line shows the products to be sold directly. The indices and descriptions of each facility used in the model formulation are described in our previous study [22]. EFB, PKS and POME are the three major palm-based biomass for energy and material products conversion. EFB has the most flexible conversion pathways as it can be used as a feedstock for all pre-processing facilities. By contrast, the PKS conversion pathways exclude extraction, DLF production and composting technology. PKS is unfavourable to the extraction process and composting due to its low contents of cellulose, hemicellulose and nutrient for soil amendments compared with EFB [37,40]. Low cellulose content indicates that PKS has a low toughness value, which makes it unsuitable for fibre applications [41,42]. The conversion pathways of POME are anaerobic digestion to produce biogas and further processing to produce electricity. Figure 3.3 shows the distribution of mills and processing facilities in Peninsular Malaysia. Peninsular is chosen as a pilot study because the land use for oil palm plantation has reached its maximum capacity. Besides, 76% of the Malaysia population resides here and thus it is important to identify possible pathways to optimise the profitability and sustainability of oil palm biomass business. Since East Malaysia accounted for 53% of oil palm planted area, the future of this work will attempt to extend the analysis to include East Malaysia and compare its biomass value chain with West Malaysia.In this study, only 146 out of 246 palm oil mills in Peninsular Malaysia are considered as suppliers of EFB. The amount of EFB, PKS and POME is 22%, 6% and 70%, respectively, of the amount of FFB processed based on the estimation made by Hamzah et al. [14] and Akhbari et al., [43]. The locations of palm oil mills and processing facilities for EFB and PKS (pre-processing, main processing, further processing 1 and further processing 2) in Peninsular Malaysia are based on our previous study Rubinsin et al., [22]. For POME, the anaerobic digestion considered is currently in operation in Peninsular Malaysia. In this study, only 96 biogas plants with known location information in Peninsular Malaysia were considered [44]. The remaining biogas plants that with unknown location (~12 plants) and those that are located in Sabah and Sarawak were excluded in this study . Both anaerobic digestion and biogas are assumed in the same location. Peninsular Malaysia is divided into 65 grids with a size of 50 km × 50 km, and therefore, the distance between any two facilities is calculated using the grid distances.

The integrated model developed is used to examine different scenarios in the oil palm industry. Four cases will be considered, and the optimal solution from each case will be discussed. The objective for Case A is to maximise the economic benefit by minimising the cost to generate high profit. In Case B, an expert-based optimal solution is obtained by trading off between the economic and the environmental impact. In Case C, what-if analysis is used to investigate how the changes in the production level of a certain product will affect the results of the optimal solutions of the value chain. Lastly, Case D is the overview of the interaction of the value chain with the EFEW nexus. Based on the constraints and requirements in each case, the model will select the technologies to be considered in the value chain. The optimum value chain pathways and biomass or product distribution around peninsular Malaysia are presented.

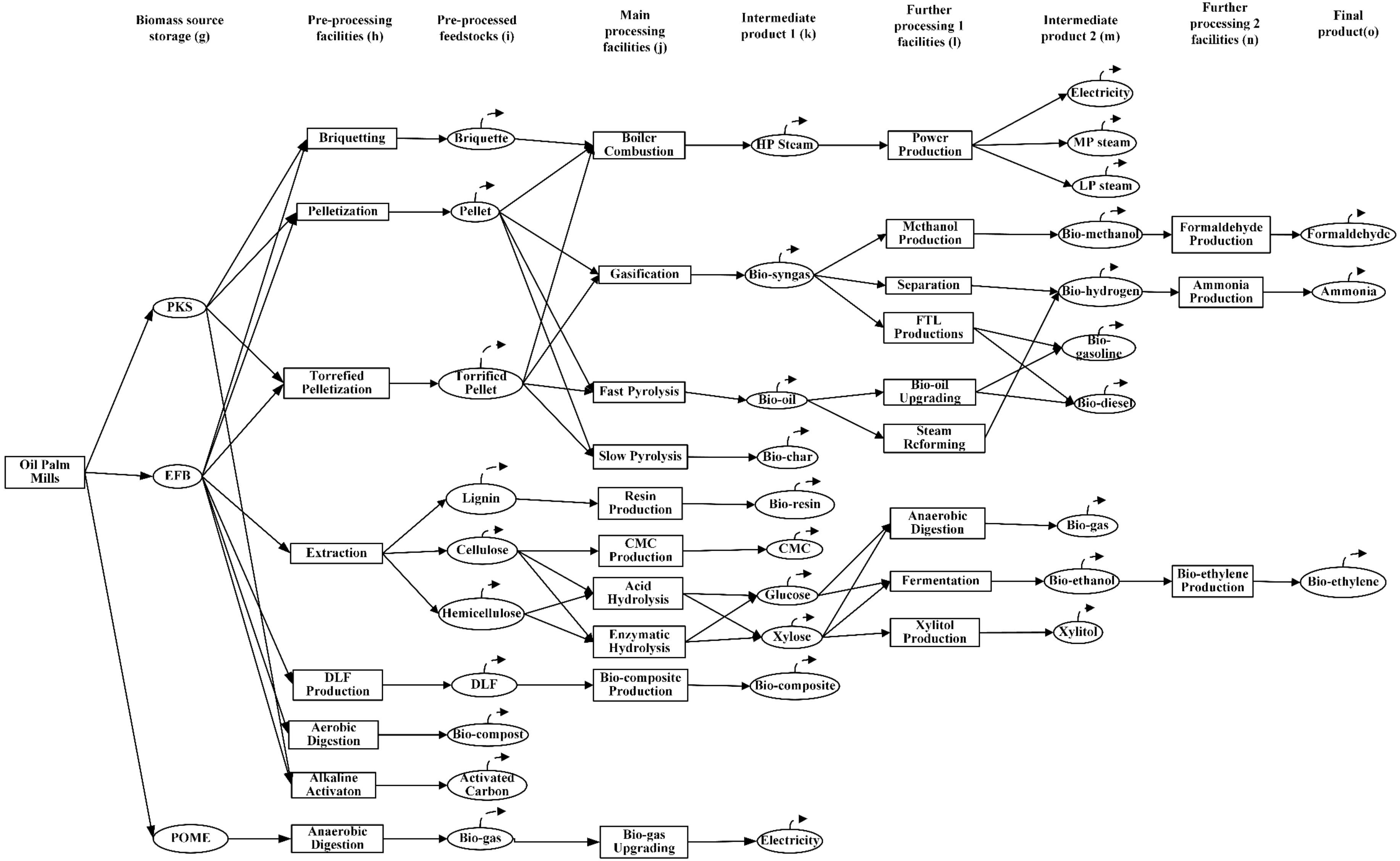


Figure 3.2 Value web pathways for EFB, PKS and POME

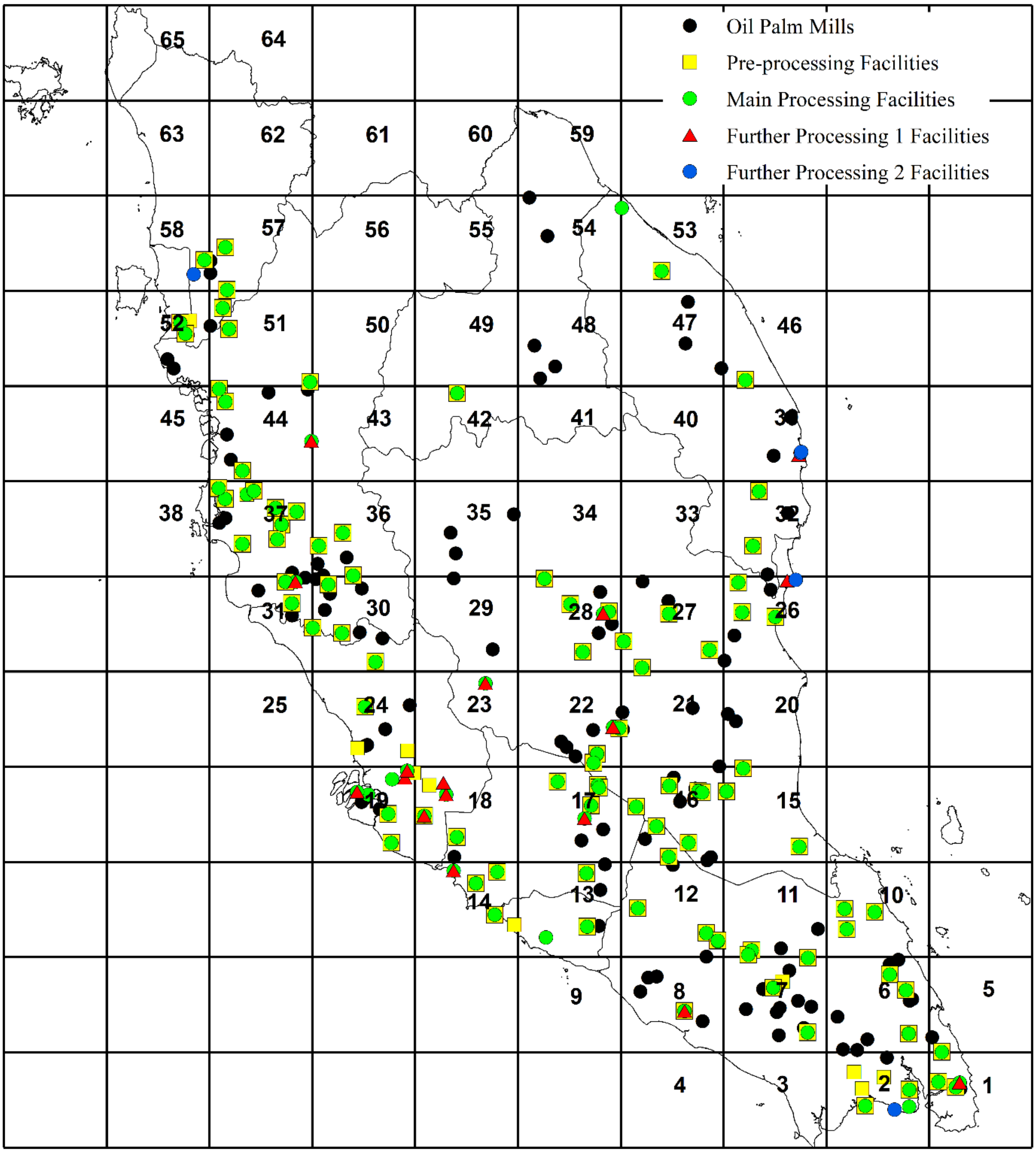


Figure 3.3 Peninsular Malaysia is segregated into 65 grids containing palm oil mills and processing facilities locations

3.2 Case A: Maximise profit of the value chain model

Case A discusses the scenario of which economic benefit is maximised with demand satisfaction of all products. The optimal pathways for the case study are shown in Figure 3.4. The products are generated based on the selected conversion technologies. The distribution of biomass and products in Peninsular Malaysia is shown in Figure 3.5. The blue, red and green lines indicate the biomass feedstock of EFB, PKS and POME, respectively.

The optimal pathways of this case show that all pre-processing facilities are selected to produce pre-processed feedstocks. The model suggested that selling most of the pre-processed feedstocks could help increase the overall profit of the value chain. Selling of DLF is not recommended because the bio-composite has a high selling price. However, the decision on selling or transporting the products to the next processing is determined and prioritised by demand satisfaction before the selling prices. This decision is also applicable to the selection of processing facilities in the value chain. The main processing facilities, further processing 1 facilities and further processing 2 facilities selected in the value chain have a lower production cost than other facilities. There is also no further processing of bio-oil through bio-upgrading facilities because the production of bio-gasoline and bio-diesel from bio-syngas through Fischer- tropsch liquids (FTL) productions can satisfy the bio-gasoline and bio-diesel demand. Exclusion of unnecessary processing facilities would reduce the production cost and contribute to the reduction of the overall cost. In addition, the unselected facilities in the value chain can be used as a backup facility in case of failure or technical maintenance of the selected facilities [45].

There are 25, 56 and 100 selected mills to supply EFB, PKS and POME, respectively. The total amounts of EFB and PKS utilised from the mills are 390,196 and 781,423 tonnes/year, respectively. The total amount of PKS supplied to the pre-processing facilities is higher than that of EFB because of its lower moisture content. Therefore, PKS is preferable for pellet, torrefied pellet and briquette production. There is a slight increment of 4.26% for solid biomass utilisation in this study compared with case study A in our previous study Rubinsin et al., [22]. The increment is because of the PKS considered in this study compared with our previous study, which only considered EFB. In addition, this model also includes POME in value chains. Hence, more biomass can be utilised compared with our previous study. For POME, 12,409,465 tonne/year is utilised. Approximately 15,260,461 tonnes/year of PKS and EFB and 26,670,735 tonne/year of POME remain unutilised due to the limited facilities available and the capacity limitation of processing facilities in Peninsular Malaysia. Thus, more pre-processing facilities are required to utilise all the remaining EFB and PKS available in Peninsular Malaysia. For this case, the government should play an important role in promoting this biomass to attract oil palm industry players to actively tap this source of renewable energy.

Figure 3.6 shows that the transportation cost can be minimised by selecting processing facilities near raw material supplies. The distribution lines of PKS from mills to pre-processing facilities are more than those of EFB because PKS is preferable for the production of briquette, pellet and torrified pellet. Thus, more PKS distribution lines could be seen in grids 55 and 57. The reason is that the pre-processed facilities in the grid have a higher processing capacity. Moreover, some PKS take a long distance to be processed to pre-processing facilities. This case could generate more transportation cost, but through these decisions, more pre-processed feedstocks can be sold to gain more profit. Most of the distribution lines from the main processing facilities until further processing 2 facilities come from EFB utilisation. Grid 19 shows more distribution because most of the main processing facilities are located in this grid. Not all grids are occupied with processing facilities, especially in the eastern region. There is a great potential to further reduce the transportation cost by increasing the biomass processing facilities or installation in this region. However, the installation of new facilities will result in high capital investment, which will pose a major business risk and long payback period [35].

One hundred mills are selected in the value chain for biogas production from POME through anaerobic digestion. These mills are in the same location as or located near the anaerobic digestion facilities. Thus, the distributions of POME and its associated products are in the same grid. This decision could minimise transportation costs and technical issues to transport POME. All 96 of anaerobic digestion and biogas upgrading facilities are considered in the value chain. The electricity demand from biogas is based on the current capacity of the biogas upgrading facilities that are supplied by the biogas from anaerobic digestion. Therefore, the electricity generated from the biogas upgrading facilities can be sold and distributed to areas near the facility. In the case of transportation, the electricity from biogas can be supplied to power stations. However, the capacity of power stations and distribution of electricity using power grids need to be taken into consideration. These decisions are out of the scope of this study, and further studies are recommended [46]. From this result, the value chain could help solve the unutilised POME issue in Malaysia whilst obtaining economic benefits. The POME utilisation strategies in this value chain can encourage mill owners to install biogas-capturing facilities to prevent methane gas emissions and can be used for electricity production and revenue generation. In a typical 60 tonne per hour of mill operation, approximately 300,000 m^3 of POME could be produced, resulting in annual GHG emissions of 37,000 to 52,000 tonnes of CO_2eq. Therefore, the implementation of biogas facilities could help reduce GHG emissions and the intolerable odour from the ponding system [47]. Loh et al., [49] reported that building biogas facilities in all mills is Malaysia's initiative towards environmental sustainability. Different sets of standards have been implemented in conjunction with the sustainability of the industry, including the Roundtable on Sustainable Palm Oil (RSPO) and Malaysian Sustainable Palm Oil (MSPO). Both standards introduced certificates to guide industry stakeholders to prioritise with sustainable practices. Hence, the environmental impact of POME utilisation needs to be monitored in order to fulfil the RSPO and MSPO requirements. Another government initiative in 2010 was through Entry Point Project No. 5 under the National Key Economic Areas (NKEA), which aims to achieve biogas plant in all oil palm mills in Malaysia by 2020 [50]. However, the installation of biogas facilities is still progressing slowly because of factors such as high cost, technical issues, transportation problems and lack of social awareness. In 2017, approximately 20% of the palm oil mills with biogas capturing facilities were installed [37]. The programme was reviewed in 2018 by the newly elected government. In 2019, Sustainable Energy Development Authority (SEDA) under the then Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC) has released the quota of 30 MW Feed-in-Tarif (FiT) e-bidding for biogas. However, the displacement cost and FiT for biogas are not viable, especially to those biogas plants that were located away from the grid [38]. In this study, the production cost of anaerobic digestion and biogas upgrading to electricity is 0.1531 USD/Nm^3 biogas and 300 USD/MW electricity, respectively. These production costs are higher compared with those of the ponding system [51,52]. In the duration between year of 2007 to 2019, a cumulative of 125 biogas plants in palm oil mills were in operation. There is still a lack of acceptance of biogas technology due to its expensive investment cost and less attractive of return on investment. For this case, social awareness on the importance of green development and sustainability is needed amongst Malaysians [38,50]

The value chain model demonstrates the economic benefits of oil palm biomass utilisation. The EFB, PKS and POME considered in this study can be utilised together from mills around Peninsular Malaysia to gain economic benefits. In addition, more bio-products could be produced from different biomass sources. The biomass, transportation and production costs from satisfying the demand of the products generated by the value chain are shown in Figure 3.6. The results are compared with those of our previous study Rubinsin et al., [22] as both studies use the same cost calculation method. However, the present study excludes the emission treatment cost. The CO_2 emissions generated in this study are not treated but are considered as a climate change impact in the value chain. The results of this study show that the total cost is 19% higher than that of our previous study. The profit of this study also shows a profit increment to 267,116,398 USD/year with a profit margin of 62% compared with that of our previous study with a profit margin of 47%. This finding implies that the model used in this study is more profitable than that of our previous study. The production cost in previous study is slightly higher than that in this study because of the many processing facilities selected. Moreover, the exclusion of the emission treatment cost in this study lowers the production costs. The biomass and transportation costs are higher in this study because of the multiple biomasses considered. Therefore, from these results, the value chain model in this study is able to reduce the total cost and achieve good profit margin by reducing the number of processing facilities considered. This case study shows that the oil palm biomass is capable to fulfil the products demand through the processing facilities around Peninsular Malaysia whilst achieving economic benefits. The next case study discusses the economic and environmental impacts based on the experts' qualitative value judgements, with the aim to maximise the economic benefits and simultaneously minimise the CO_2 emissions generated and water consumption as climate change impact and water impact, respectively.

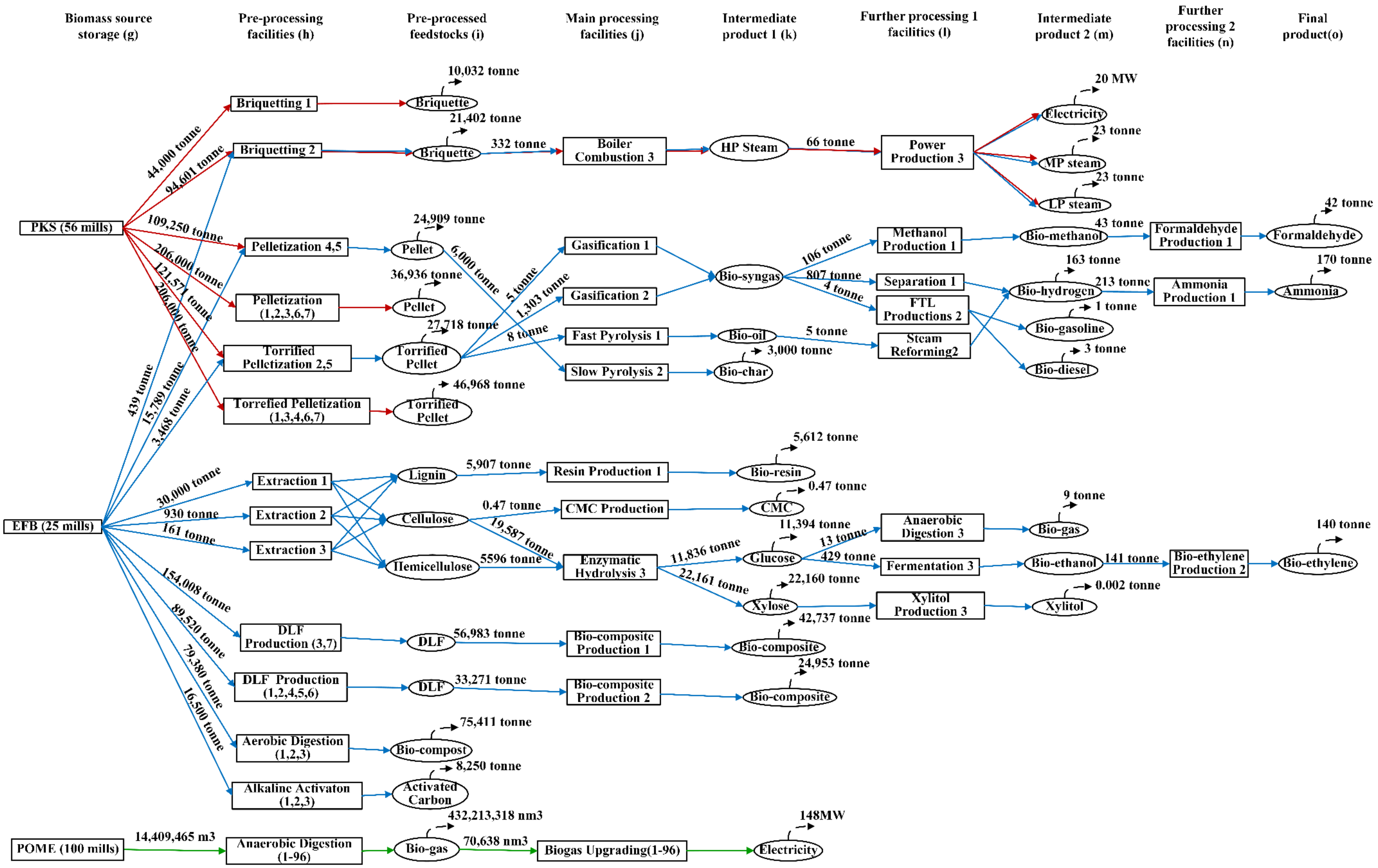


Figure 3.4 Optimal Pathways for Case A

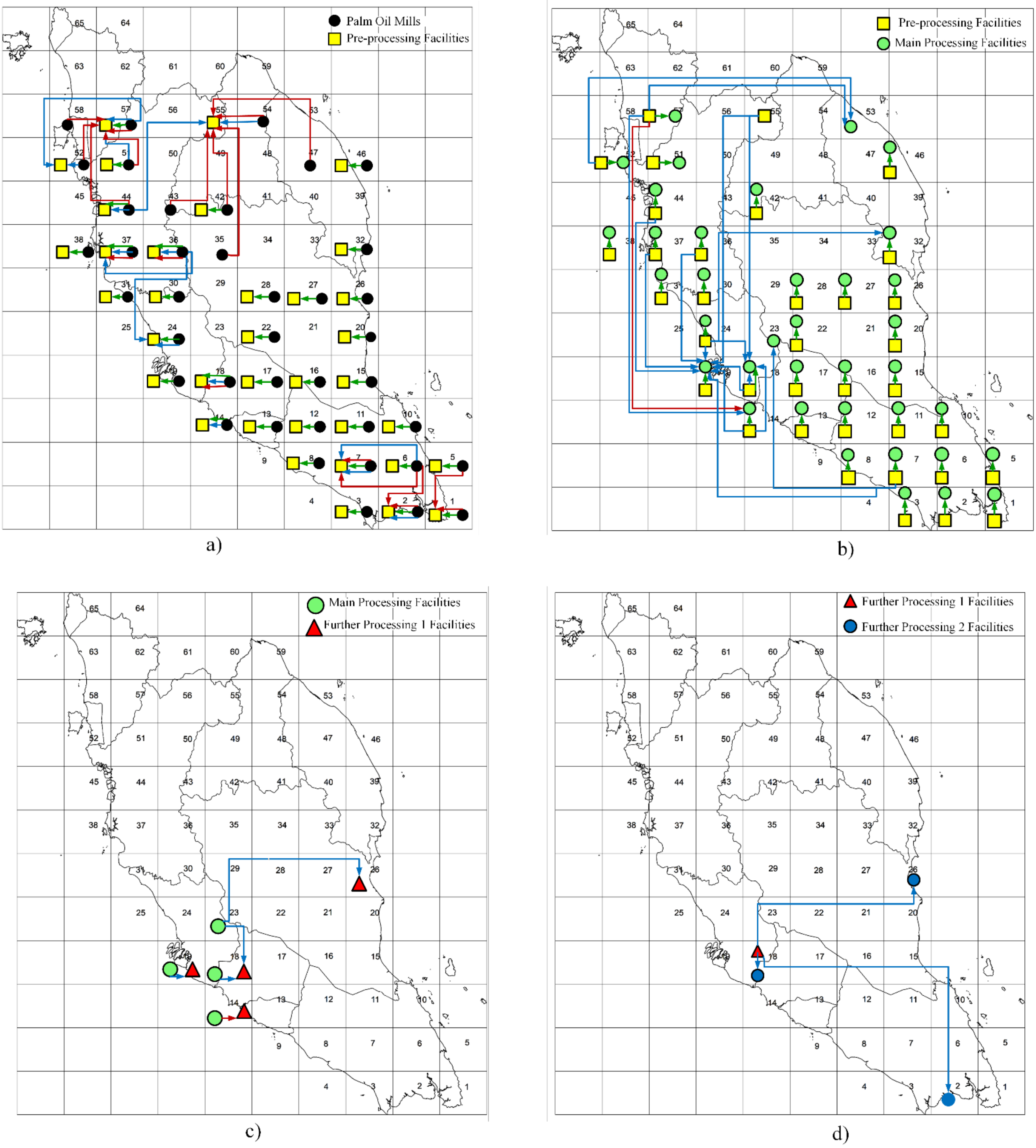


Figure 3.5 Biomass and Products distribution between facilities for case A at a) palm oil mills to pre-processing faciltities, b) pre-processing facilities to main processing facilities c) main processing facilities to further processing 1 faciltities and d) further processing 1 facilities to further processing 2 facilities where the distribution line of PKS, EFB and POME are in red, blue and green, respectively.

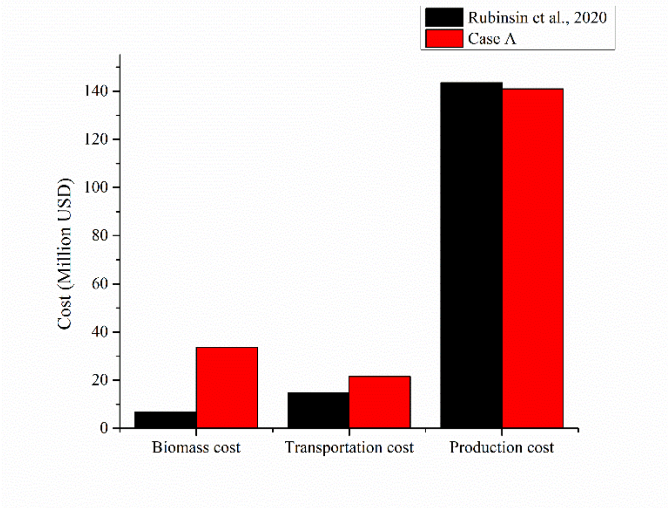


Figure 3.6 Biomass, transportation and production costs comparison between Rubinsin et al. 2020 and Case A

3.3 Case B: Maximum profit with optimal solutions based on expert judgement

In Case B, economic, climate change and water impacts are weighted by 32 experts based on a short survey. Figure 3.7 shows the demographic of the 32 experts which shows most of experts are from industries followed by academician and government agencies or policy makers. The weights from FAHP are summarised in Table 3.1, which shows that the priority given for economic benefits and climate change is higher compared with that for water impact. Therefore, the optimisation model will give more priority to the design of the value chain with a lower impact in economic and climate change. Malaysia is moving forward to increase the country's income. However, the increased generation of economic benefits will also increase GHG emissions [53,54]. Therefore, balancing the trade-off between economic benefits and climate change is needed. The least priority given for water impact could be because Malaysia is located in an abundant water region and is rich in water resources [55]. Therefore, the economic benefits and climate change are critical to ensure that Malaysia could achieve a green economy. Table 3.2 shows the optimal solutions for different objectives. The minimum climate change impact and minimum water impact are also calculated to obtain the normalisation factor for the expert-based solution. The normalisation factor is the ratio of economic benefits to climate change impact and water impact. The normalisation factor is used so that all impacts are on the same scale before the weights from the FAHP can be used to reflect the relative importance between objectives. Based on the results, the normalisation factor is 1, 8.09 and 7.78 for maximum economic benefits, minimum climate change impact and minimum water impact, respectively. Hence, based on the normalisation factor and the weights from the FAHP, the model is designed to select the optimal pathways that generate profit whilst achieving minimum environmental impact.

The expert-based solution optimal pathways and the biomass and product distribution are shown in Figures 3.8 and 3.9, respectively. The blue, red and green lines indicate the biomass feedstock of EFB, PKS and POME, respectively. The total number of mills as EFB and PKS supplier considered in this case is only 15, and the amount of biomass utilised is 127,539 tonnes/year, which is 89% lower than that of Case A. As shown in Figure 3.8, there are also less biomass or product distributions around Peninsular Malaysia compared with those of Case

A, which minimise the transportation cost and CO_2 emissions generated. For POME, the number of mills considered is the same as that in Case A. The amount of EFB supplied to the pre-processing facilities is higher than that of PKS because EFB has a lower biomass cost than PKS. Although the pre-processed feedstocks produced from EFB have a higher production impact than those from PKS, the utilisation of more EFB could help reduce the total costs and generate more profit. Moreover, EFB is preferable for other products such as bio-oil, bio-ethanol, glucose and bio-char.

The model suggests to minimise the biomass supply to reduce the environmental impact generated from it. A significant reduction of the biomass supply will also decrease the total amount of products sold. The result also shows that in order to minimise the environmental impact, a 34% cut of the profit is needed to reduce 91% of CO_2 emissions and 97% of water consumption. The results have a similar trend with the case study by Tapia and Samsatli [23], where the reduction of environmental impact is proportional to the decline of the production level and profit. Although the production level is reduced in this study, the product demand can still be satisfied, and the economic benefits can be achieved.

The results show that the expert-based optimal solutions are capable of providing a balance between economic, climate change and water impacts based on the given expert qualitative value judgement. However, the global search for bio-products and biofuels is increasing over time [56]. Therefore, the production levels of products need to be increased to continue satisfying product demand. Given the significant production effect on the environmental impact, the next case study was performed by varying the amount of production of selected products with an objective to minimise the environmental impact. This case study could benefit decision-making in production planning in order to cope with demand uncertainty over time.

Table 3.1 Final weights of the impacts based on the experts' survey

Experts	Objectives		
	Economic	Climate Change	Water
1	0.31	0.37	0.32
2	0.50	0.26	0.24
3	0.53	0.24	0.24
4	0.61	0.19	0.19
5	0.33	0.33	0.33
6	0.33	0.33	0.33
7	0.48	0.26	0.26
8	0.50	0.25	0.25
9	0.54	0.25	0.21
10	0.45	0.33	0.21
11	0.44	0.34	0.22
12	0.42	0.42	0.16
13	0.11	0.20	0.69
14	0.61	0.31	0.07
15	0.38	0.24	0.38
16	0.33	0.33	0.33
17	0.74	0.20	0.06

18	0.33	0.33	0.33
19	0.80	0.10	0.10
20	0.54	0.27	0.19
21	0.74	0.06	0.20
22	0.33	0.33	0.33
23	0.62	0.19	0.19
24	0.06	0.74	0.20
25	0.32	0.30	0.39
26	0.09	0.45	0.45
27	0.19	0.40	0.40
28	0.23	0.12	0.65
29	0.51	0.41	0.08
30	0.58	0.26	0.16
31	0.28	0.42	0.30
32	0.38	0.33	0.29
Geometric Mean	0.37	0.27	0.24
Final Weight	0.42	0.31	0.27

Figure 3.7 Demographic Distribution of Respondents Based on 32 Experts

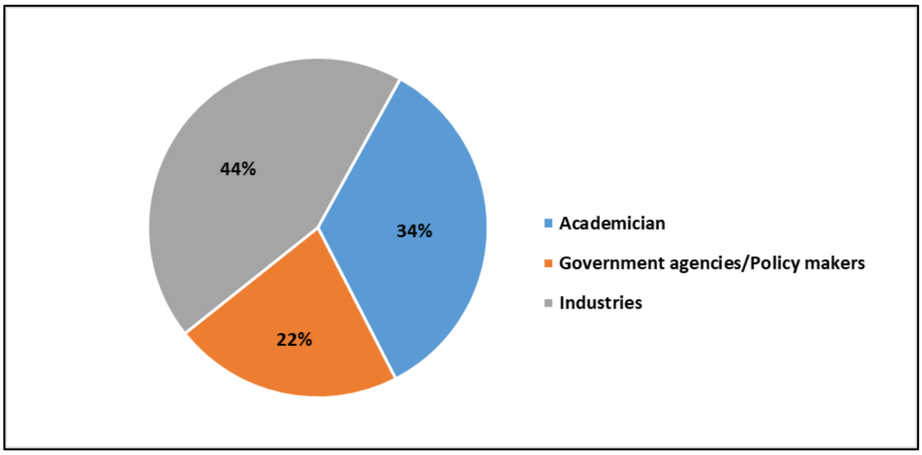
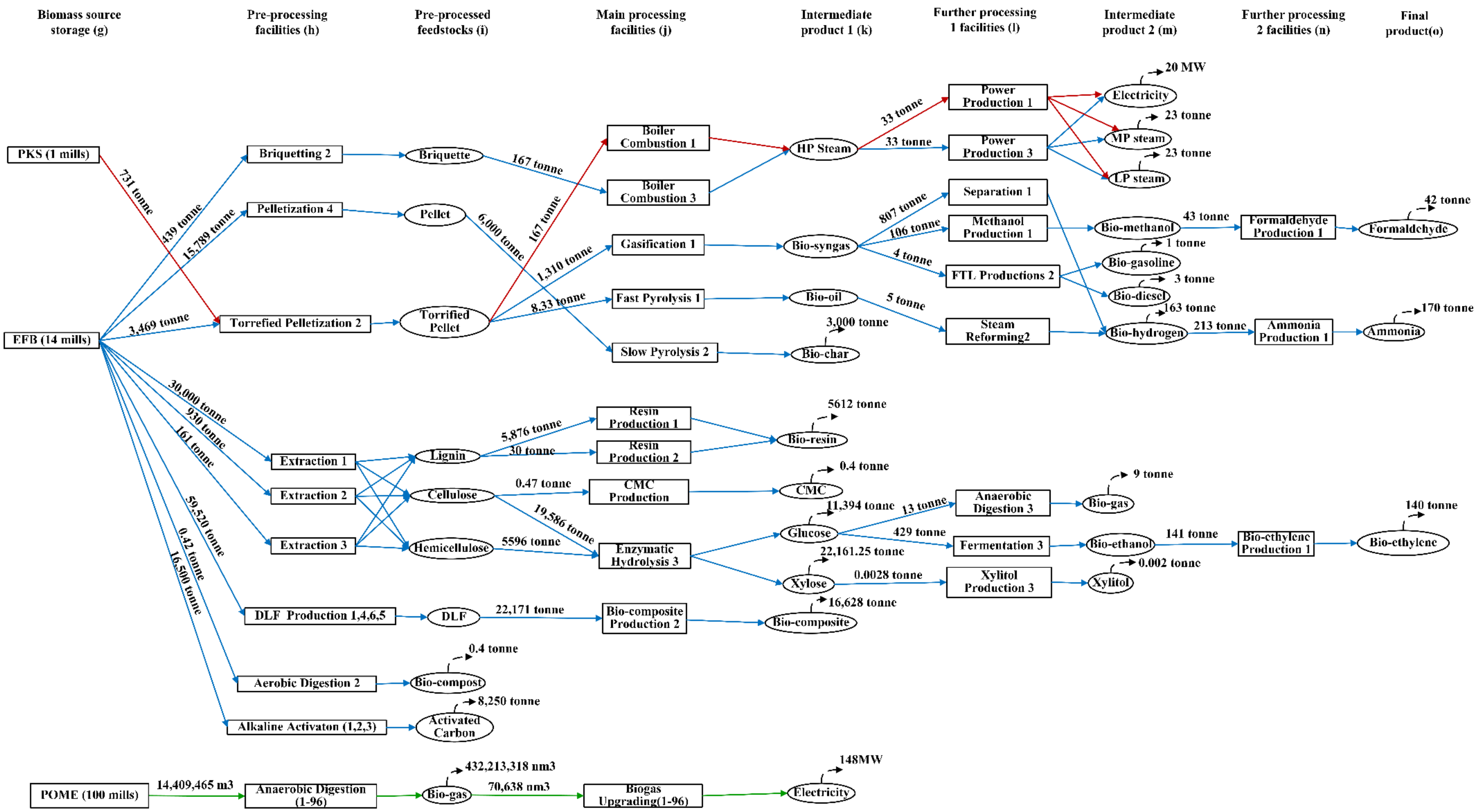


Table 3.2 Proposed optimal solutions under different objectives and expert-based solution

Objectives	Profit (Million USD)	Climate change impact (Million ton CO_2eq)	Water impact (Million m^3)
Maximum economic benefits	267.12	36.62	34.35
Minimum climate change impact	263.78	33.01	34.99
Minimum water impact	267.12	36.62	34.35
Expert-based solution	176.72	3.42	1.01



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656 Figure 3.8 Optimal Pathways for Case B

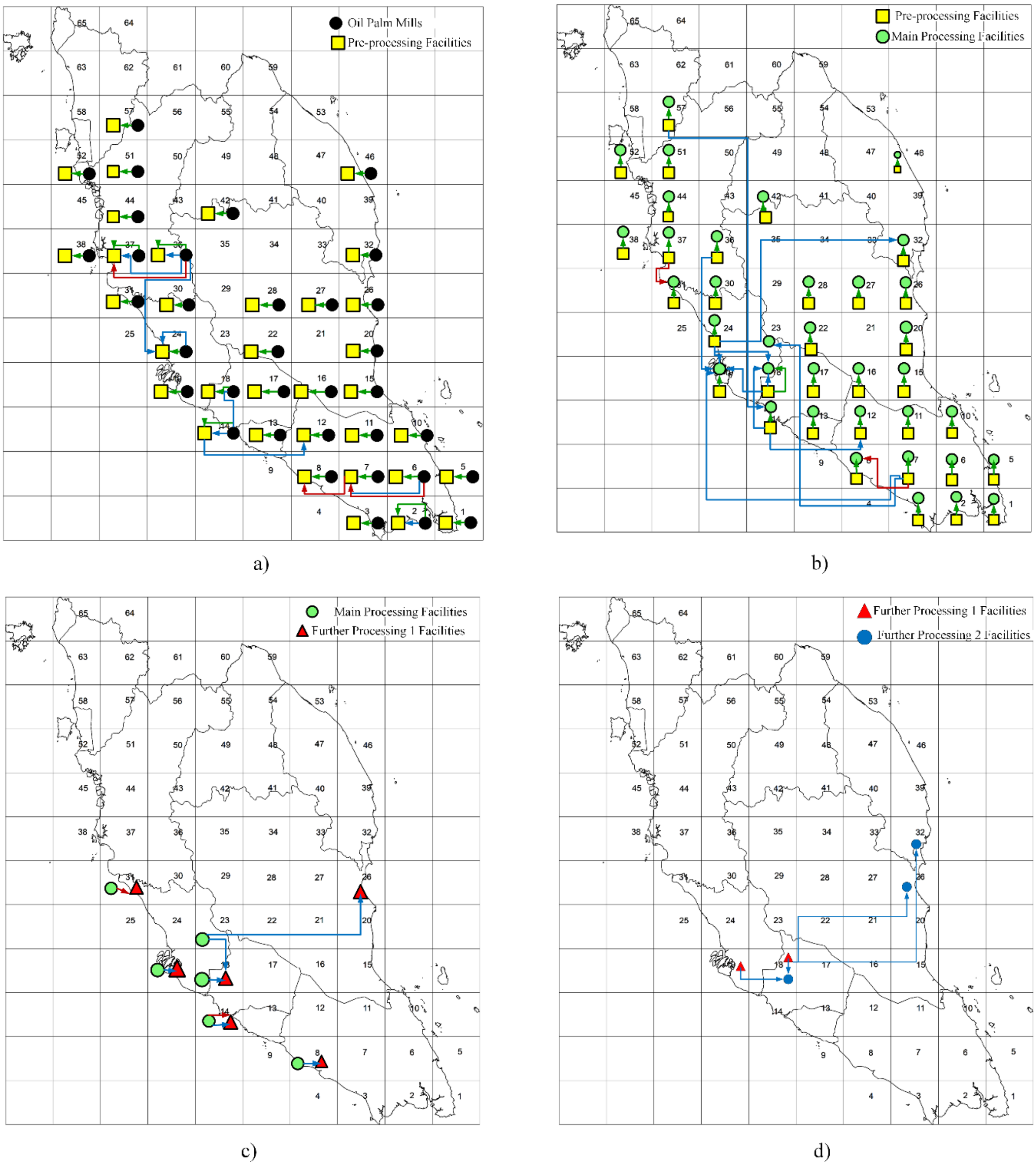


Figure 3.9 Biomass and Products distribution between facilities for case B at a) palm oil mills to pre-processing faciltities, b) pre-processing facilities to main processing facilities c) main processing facilities to further processing 1 faciltities and d) further processing 1 facilities to further processing 2 facilities where the distribution line of PKS, EFB and POME are in red, blue and green, respectively.

3.4 Case C: Production level variation with consideration of environmental impacts

The current focus of Malaysia is to improve environmental management through cleaner production. However, achieving the environmental objectives whilst experiencing fluctuation in production level changes is a challenging task [57,58]. Therefore, this case study provides insights on how companies can achieve environmental requirements by controlling the production rate in the value chain. Two scenarios are discussed in this case to illustrate the production level changes in a company. Scenario 1 assumes that the company experiences demand fluctuations for pellets, glucose, bio-diesel and ammonia. Demand fluctuations are a common challenge in any production system. Scenario 2 assumes that some of the processing facilities experience shutdown or are undergoing technical maintenance. Therefore, by using optimal pathways in Case B as a reference, several facilities will be set as no production activity to see the effects on environmental impact. For real situations, a shutdown is unlikely to happen because it is an extreme situation that could affect the entire profit. Facility shutdown for technical maintenance is a valid reason but also incurs losses [59]. Moreover, it can lead to product delivery delay to the customer. Both scenarios are the value chain disruptions that could happen unpredictably. For example, due to the COVID-19 outbreak, many countries have experienced a significant loss due to closures of production facilities. Many companies are unprepared to handle the disruptions caused by COVID-19. The lockdown orders in every nation result in demand disruptions where the demand for essential products such as food and medicine is rapidly increasing and non-essential products have less or no demand [60]. Therefore, conducting a scenario production planning is essential to ensure adequate production planning and scheduling during periods of disruptions. Table 3.3 shows the results for the two scenarios that are considered in this study. Other products and processing facilities could be selected as well because the purpose of this analysis is to observe the effects on the optimal value chain solutions by manipulating the production level. The minimum amount of 33 million tonne CO_2eq of CO_2 emissions and 34.35 million m^3 of water consumption in Case B is taken as an environmental standard in this study.

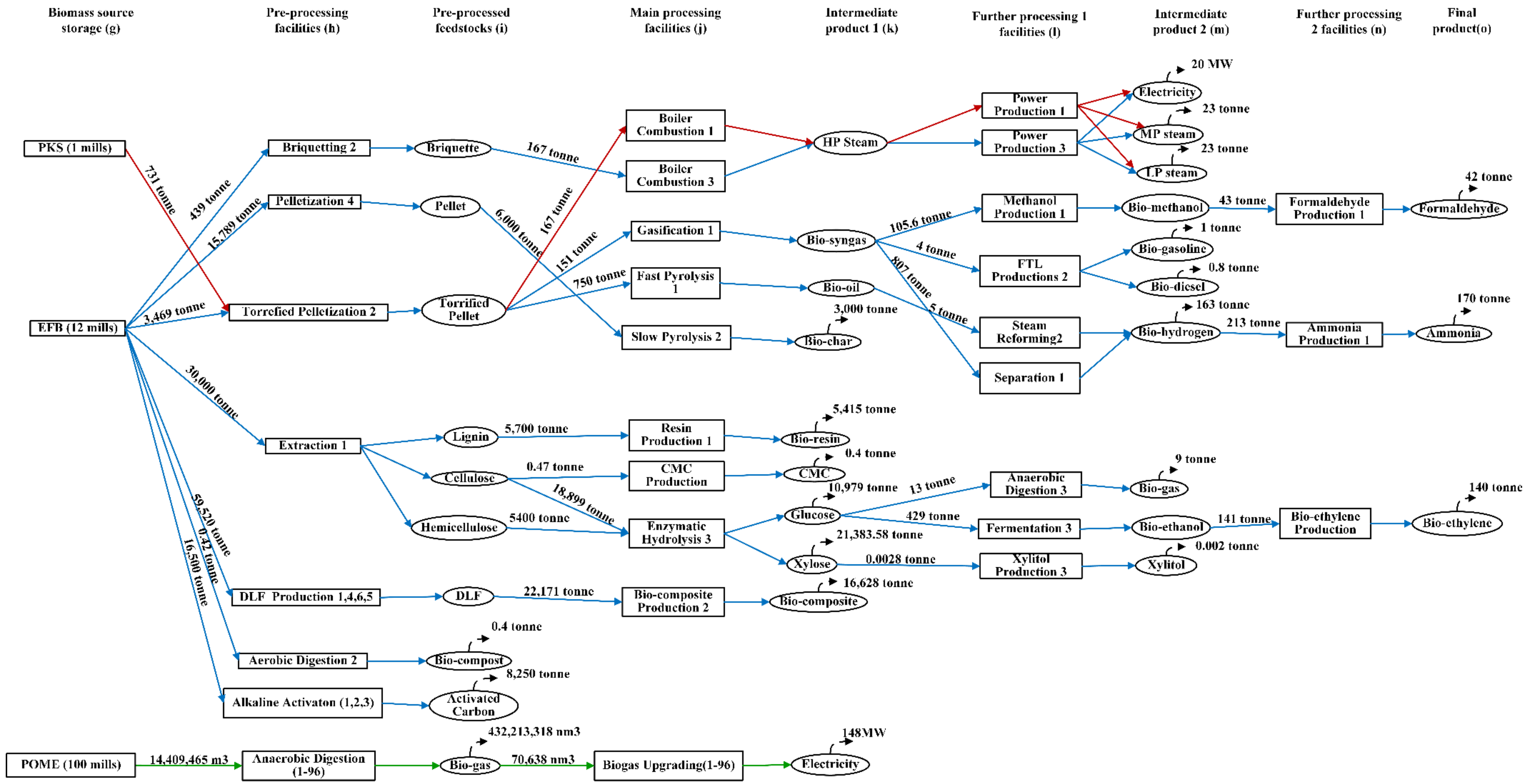
The results for scenario 1 in Table 3.3 show that as the demands increase, the profit, CO_2 emissions and water consumption also increase. For scenarios 1(a) and 1(b), the profits increased by 52%, compared with Case B. However, the increment of the processing capacity of extraction facilities to produce glucose is needed to avoid infeasible solution in the model. The capacity is suggested to increase by 281,869 tonnes/year in order to produce 50% more glucose. In scenario 1(c) and scenario 1(d), the reduction of other products result in an infeasible solution. The amount of pellets that have been reduced is enough for more bio-methanol production through methanol production plant but the demand for biochar cannot be satisfied. The solution to the problem is to reduce biochar production by 20% and 50% for scenario 1(c) and scenario 1(d), respectively. However, a decreased supply of biochar could affect the sales of the value chain. The profit generated for scenario 1(c) and scenario 1(d) are 1% and 2%, slightly lower compared with that in Case B. For this case, increasing the price of the biochar could be a solution to increase the profit. Therefore, demand planning is a critical factor to consider in the value chain. A practical plan could help companies to accurately forecast the demand in the future and determine the product prioritisation [61]. The result from scenario 1 implies that more profit can be generated when production is increased. However, the value chain needs to be modified, including the processing capacity size and demand satisfaction of all products, in order to address interruptions that may occur. Capacity planning should be considered in the value chain. A decision of finding the trade-off between capacity shortage and capacity excess needs to be taken into account. Capacity expansion, wherein new facilities are added into the process, is possible to meet the growing demand. However, some companies may have difficulty in conducting capacity expansion due to high cost, technology advancement, complicated process and risk to capacity scarce and wasting [62].

Figure 3.10 shows the optimal pathways for scenarios 2(a) and 2(b). In scenario 2(a), extraction 2 and extraction 3 are selected to observe the effects to the value chain when only one facility is left to be considered for the particular process. For instance, the exclusion of extraction 2 and extraction 3 will give significant effects to the amount of product associated with it. The total amount of EFB supplied to the pre-processing facilities is 1% lower than that of Case B. Excluding extraction 2 and extraction 3 limits the EFB supplied up to 30,000 tonnes/year, which is the maximum capacity that extraction 1 can take. The reduction of the total production in this scenario results in a slight decrement of 2% of the profit, 0.2% of CO_2 emissions and 1% of water consumption compared with that in Case B. The result of scenario 2(b) is the same as that of Case B. The significant differences in this scenario are the replacement of FTL production 2 and fermentation 3 facilities to FTL production 1 and fermentation 2, respectively. In a real situation, the substitution of a facility to another facility is likely to happen. However, when no other facility is available, the current facility needs to be in operation in order to fulfil product demand [63]. In this scenario, FTL production and fermentation facilities need to be considered in the value chain in order to fulfil the demand for bio-gasoline, bio-diesel and bio-ethanol. Moreover, the substitution of the facility does not provide any effect to the value chain as there are multiple facilities in the value chain.

Both scenarios can illustrate the uncertainty that might happen in the value chain. Demand changes often occur because the market will change over time. Shutdown of facilities is unlikely to happen, but production planning is essential to prevent losses in economic benefits. CO_2 emissions and water consumption for all scenarios are proportional to the production rate of the product. The production at each facility has its environmental footprints. Thus, increasing the production level will increase the environmental impact. Table 3.3 shows that the average CO_2 emissions generated and water consumption in this scenario are 2.99 million tonnes CO_2eq of CO_2 emissions and 0.54 million m^3, respectively. Therefore, it is considered acceptable as the amount is below the environmental standards. From these results, the changes in the value chain will generate different optimal solutions.

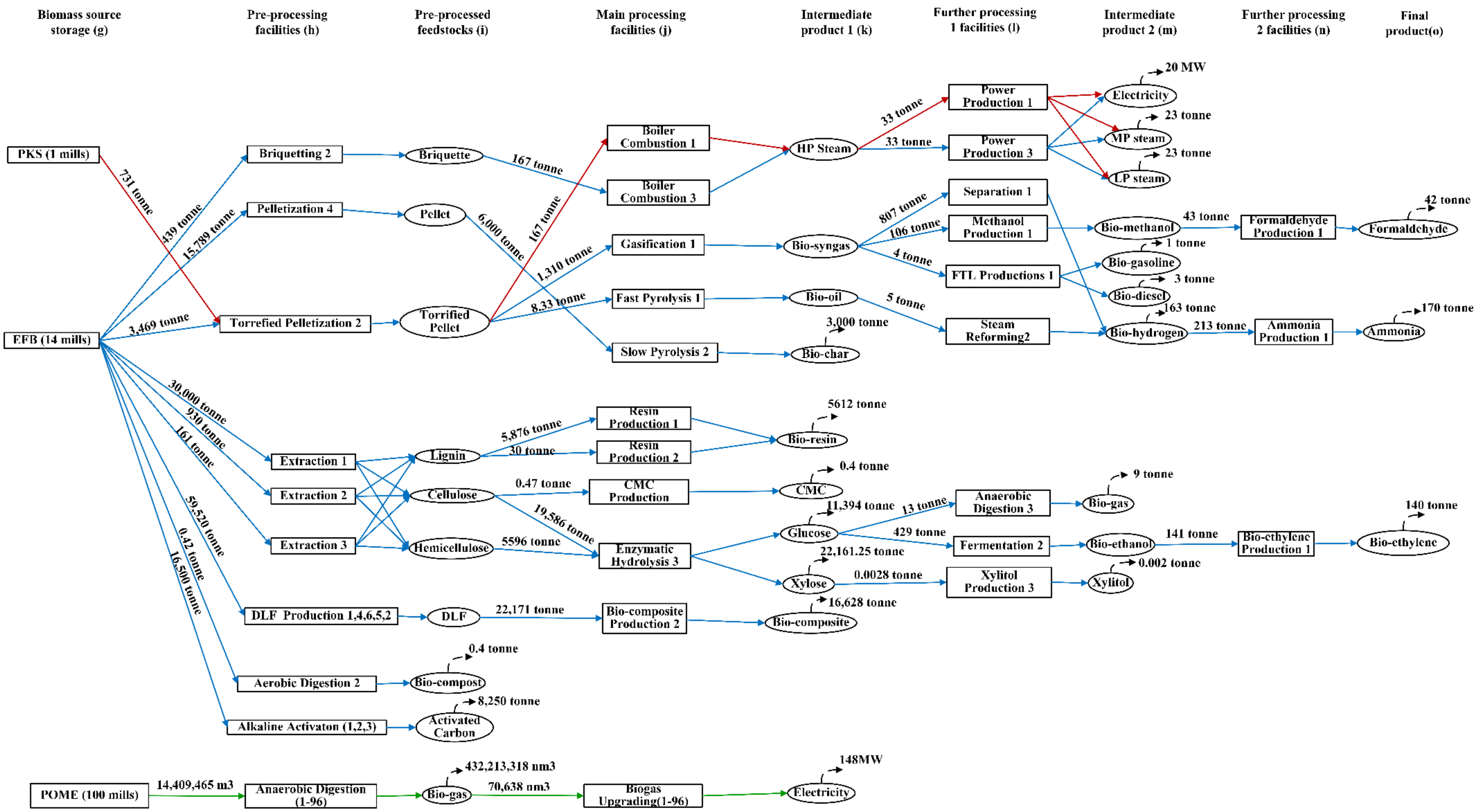
Table 3.2 Scenarios and the model results

Scenarios 1:	Model input changes	Profit (Million USD)	Climate change impact (Million ton CO_2eq)	Water impact (Million m^3)
Scenario 1: Demand disruptions (Change production level of pellet, glucose, bio-methanol and ammonia from Case B)	a) Increase 50% production of all product	268.52	3.64	1.25
	b) Increase 50% glucose production and maintain other product	268.47	3.62	1.22
	c) Increase 75% of bio-methanol production and decrease 20% of other product	175.14	3.40	0.99
	d) Decrease 50% production of all product	172.77	3.37	0.95
Scenario 2: Operational Disruptions	a)Setting extraction 2 and extraction 3 facility capacity to zero	173.26	3.41	0.99
	b) Setting FTL production 2 and fermentation 3 facilities capacities to zero.	176.71	1.01	3.42



Biomass source storage (g)
Pre-processing facilities (h)
Pre-processed feedstocks (i)
Main processing facilities (j)
Intermediate product 1 (k)
Further processing 1 facilities (l)
Intermediate product 2 (m)
Further processing 2 facilities (n)
Final product(o)
PKS (1 mills)
EFB (12 mills)
POME (100 mills)
731 tonne
439 tonne
15,789 tonne
3,469 tonne
30,000 tonne
59,520 tonne
0.42 tonne
16,500 tonne
14,409,465 m3
Briquetting 2
Pelletization 4
Torrefied Pelletization 2
Extraction 1
DLF Production 1,4,6,5
Aerobic Digestion 2
Alkaline Activaton (1,2,3)
Anaerobic Digestion (1-96)
Briquette
Pellet
Torrified Pellet
Lignin
Cellulose
Hemicellulose
DLF
Bio-compost
Activated Carbon
Bio-gas
167 tonne
6,000 tonne
167 tonne
151 tonne
750 tonne
5,700 tonne
0.47 tonne
18,899 tonne
5400 tonne
22,171 tonne
0.4 tonne
8,250 tonne
432,213,318 nm3
70,638 nm3
Boiler Combustion 1
Boiler Combustion 3
Gasification 1
Fast Pyrolysis 1
Slow Pyrolysis 2
Resin Production 1
CMC Production
Enzymatic Hydrolysis 3
Bio-composite Production 2
Biogas Upgrading(1-96)
HP Steam
Bio-syngas
Bio-oil
Bio-char
3,000 tonne
Bio-resin
5,415 tonne
CMC
0.4 tonne
Glucose
10,979 tonne
Xylose
21,383.58 tonne
Bio-composite
16,628 tonne
Electricity
148MW
105.6 tonne
4 tonne
807 tonne
5 tonne
13 tonne
429 tonne
0.0028 tonne
Power Production 1
Power Production 3
Methanol Production 1
FTL Productions 2
Steam Reforming2
Separation 1
Anaerobic Digestion 3
Fermentation 3
Xylitol Production 3
Electricity
20 MW
MP steam
23 tonne
LP steam
23 tonne
Bio-methanol
43 tonne
Bio-gasoline
1 tonne
Bio-diesel
0.8 tonne
Bio-hydrogen
163 tonne
213 tonne
Bio-gas
9 tonne
Bio-ethanol
141 tonne
Xylitol
0.002 tonne
Formaldehyde Production 1
Ammonia Production 1
Bio-ethylene Production
Formaldehyde
42 tonne
Ammonia
170 tonne
Bio-ethylene
140 tonne

(a)



(b)

Figure 3.10 Optimal Pathways for Scenario 2

3.5 Case D: Interactions with the EFEW nexus

Concerns on environmental impact can be diminished when the oil palm biomass utilisation is linked with the EFEW nexus to meet the standard requirements [64]. The purpose of this case study is to analyse the interactions between the nexus and to identify the improvements that can be made in the value chain model for future studies. The interlinkages between the nexus in the value chain are presented in Figure 3.11. EFB, PKS and POME can be used to produce various bio-products, and they can be considered as a source of energy and food. The food-based products are CMC, glucose and xylose. CMC is known as cellulose gum and widely used in the food industry [65]. Glucose, xylose and xylitol are used as a sweetener in the food industry [66,67]. The production of these food-based products is beneficial in terms of food supply and improves livelihoods without land expansion. Moreover, the production of glucose from enzymatic hydrolysis has a synergistic effect with the production of biogas, bio-ethanol and bio-ethylene as bioenergy and biofuel products.

The interactions of biomass with energy contribute to the production of bioenergy products such as electricity, biogas, bio-ethanol, bio-methanol, bio-hydrogen, bio-gasoline and bio-diesel in the value chain. For instance, electricity production from EFB and PKS through power production and from POME through biogas upgrading can produce a total of 168 MW electricity. This finding implies that the production of electricity from renewable sources is possible. Although electricity generation from the value chain is small, it can contribute to the electricity supply in Peninsular Malaysia. Biogas contains mostly methane and CO_2, which could harm the environment. The utilisation of biogas from POME offers a great way to reduce environmental impact [68]. On the basis of these results, the value chain is capable of producing bioenergy products whilst minimising environmental impacts.

All of the products in the value chain are interconnected but compete at the same time. They also act as a feedstock for other products, which add more competition issues in their production. The production also requires water. The total water consumption of Case B is 479,555 m^3/year. This amount of water is estimated to be equal to the water supply for 6,123 people [69]. This finding implies that the high water consumption will compete with household water consumption. Therefore, better water management is important to avoid shortage of water supply to a residential area in Peninsular Malaysia and water pollution resulting from water disposal. The water consumption considered in this study affects the product yield and economic benefits. The product yield needs to be reduced to minimise water consumption, but this will also result in loss of profit. Thus, a water treatment technology should be adopted into the value chain as water recycling may help minimise the water impact. However, water treatment or water recycling is out of the scope of this study, and further studies are recommended. The total CO_2 emission generated from this study is shown in Figure 3.12. The CO_2 emissions generated in this study are higher than those of our previous study (99% higher for Case A and 93% higher for Case B). The addition of PKS and POME utilisation in the value chain increased the total CO_2 emissions. The CO_2 emissions generated are from anaerobic digestion and biogas upgrading. The results imply that the production of bio-products from oil palm biomass will produce significant CO_2 emissions and water footprint that need to be quantified and minimised.

The oil palm biomass value chain along with its interaction with the nexus has been developed to identify the trade-offs between economic benefits and the nexus. The maximum contribution of biomass to the nexus could be seen in the value chain, where the biomass is capable of producing various bio-products that are environmentally friendly. In addition, through biomass utilisation, the dependence on fossil fuels for bioenergy and biofuel products could be reduced. However, the utilisation of the biomass also generates environmental impacts. Therefore, a specific analysis on complete balance of CO_2eq is needed to carry out due to the displacement of petroleum derived products. In this study, such analysis was not considered but the models regulate the overall CO_2 emission by optimizing the overall impact to climate change, water and economic.

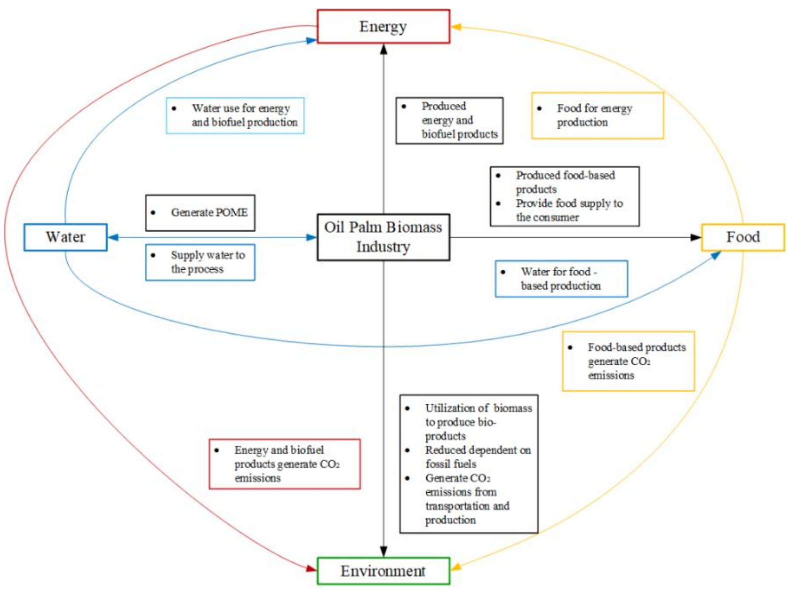


Figure 3.11 Overview of interactions of the EFEW nexus in the value chain

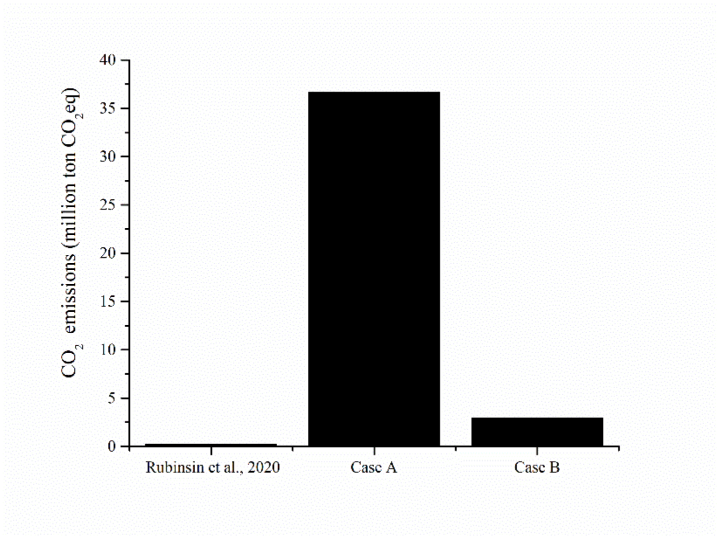


Figure 3.12 CO_2 emission generated from different cases

4.0 CONCLUSION AND FUTURE WORKS

An oil palm biomass value chain model was developed to generate expert-based optimal solutions. The optimal solutions suggested important decisions, such as production level, transportation of products, location of palm oil mills and processing facilities, degree of environmental impact and FAHP decision, to incorporate the stakeholder and expert's judgement into the value chain. Overall, the case studies demonstrated the economic benefits concerning each of the environmental impacts. The environmental impact of climate change impact and water impact is minimised whilst obtaining economic benefits. The analysis of the production uncertainty also provides important insights in order to avoid financial risks in a company. Therefore, this study could help encourage active participation of companies in the biomass industry and public–private partnerships between various industries and stakeholders in Malaysia to work together in order to achieve sustainable development goals through the oil palm biomass value chain. This study also provides insights for future policymaking related to technology deployment to convert oil palm biomass such as EFB, PKS and POME; green technology; and renewable energy.

However, future studies need to investigate the interactions of biomass utilisation and the nexus. The water recycling or water treatment system needs to be considered in the value chain. This strategy could minimise the usage of clean water that will be used for other purposes, especially for household or residential areas. Access to clean water has also become an issue of concern in Malaysia [64]. Therefore, water supply or source areas need to be included in future studies in order to identify the impact generated. Land expansion analysis was not included in this study because the study considered the available palm oil mills and processing facilities in Peninsular Malaysia. However, land use analysis should be considered in future studies because the identification of available land in Peninsular Malaysia could help in decisions regarding the installation of processing facilities. Recycling of products should also be included in the value chain. For instance, the electricity generated in the value chain can be recycled back to the processing facilities. This strategy could minimise the usage of fossil fuels as a power supply for the operation of processing facilities. For this case, the cost, technical aspects and energy distribution station should be considered. Such analysis requires extensive efforts, but in the future, the oil palm biomass value chain is expected to become more efficient and effective to be used as a decision tool in the oil palm industry.

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